Astronomy 191 - Stars 2

- Stellar classification

- Stellar Atmospheres: Low mass stars

- Stellar activity cycles: Low mass stars

- Stellar Atmospheres: High mass stars

- Interacting Stars

- Eta Carinae

read chap 4 & 5 in Charles & Seward

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Stellar Classification

• stars classified according to *spectral type* and *luminosity class*

spectral type: descriptor of (de-reddened) color of star, i.e. an indicator of stellar temperature

luminosity class: descriptor of brightness of star in a given spectral class, i.e. an indicator of stellar size, since

$$L = 4\pi R^2 \sigma T^4$$

(Stefan-Boltzmann law)

where T is the stellar temperature, R the radius and L the luminosity of the star, and σ a constant.

Sp. Type	Temperature
O	> 30000K
B	12000-30000K
A	8000-12000K
F	6000-8000K
G	5000-6000K
K	4000-5000K
M	2000-4000

Luminosity Class	Description
Iab	Supergiant
II	Bright Giant
III	Giants
IV	Subgiants
V	Dwarf (Main Sequence)

Examples: Sun G2V; Rigel B8Ia

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Stellar atmosphere – only directly observable part of a star

- can only directly observe the radiation emitted from the stellar atmosphere (except for the sun no details of the spatial structure)

- atmosphere consists of the stellar photosphere (where most of the stellar radiation is produced), plus overlying layers

- Structure of the atmosphere is dependent on the mass of the star

- Stellar atmospheres observationally studied via spectrophotometry (broad-band, narrow-band and dispersed)

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Atmospheric emission from a low mass star
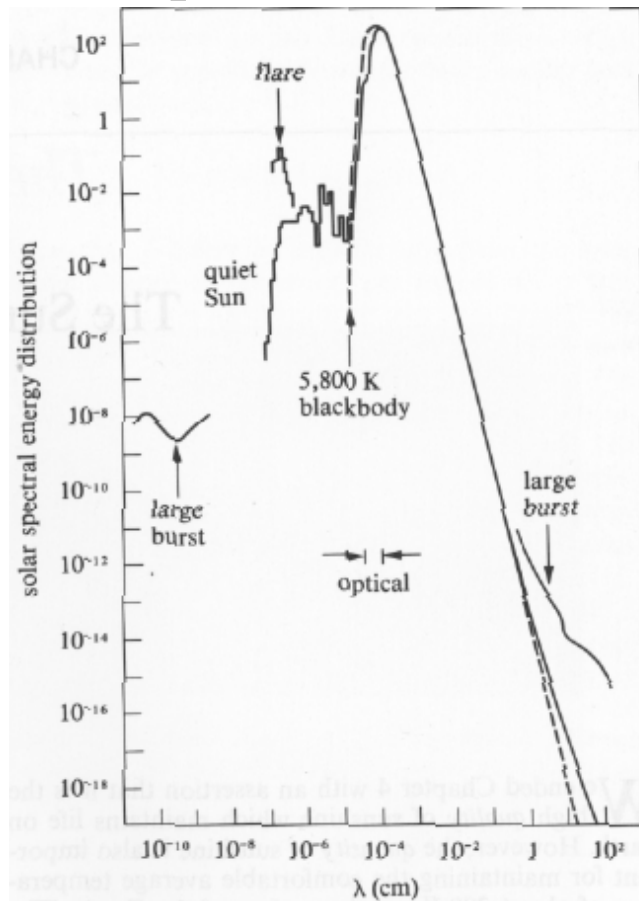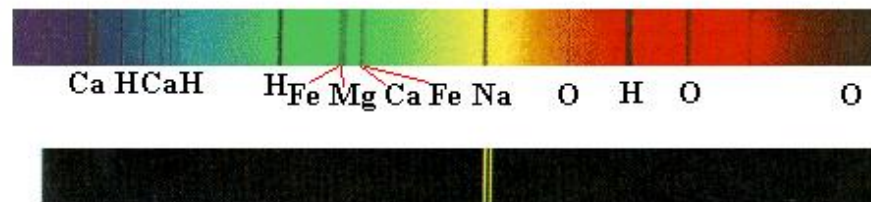

Figure 5.1. The solar spectral energy distribution.

Example: the sun
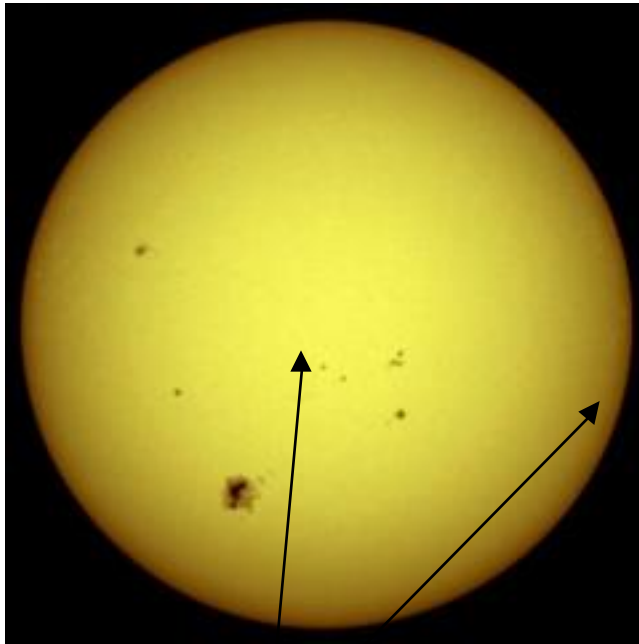
Solar Spectrum with absorption lines

Notice that the dark lines in the solar spectrum correspond to the emission lines of the various elements. This is because atoms can absorb or emitt at the same wavelengths.

Visible solar flux emphasizing the continuum and absorption line spectrum

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The Photosphere: The stellar "surface"

• Photosphere: Lowest layer of solar atmosphere; visible "surface" of the sun; place where optical depth ≈ 1

• optical depth $\tau = \int k \, dx$ along some path length dx

and k = coefficient of absorption (depends on chemical composition, density, temperature, wavelength)

• optically thick thermal emission => blackbody emission

• in the interior, photons don't move very far before scattering off an atom; at the photosphere, the density, temperature are low enough that the chance of a photon scattering off an atom is low.

• photospheric spectrum: continuum + absorption lines

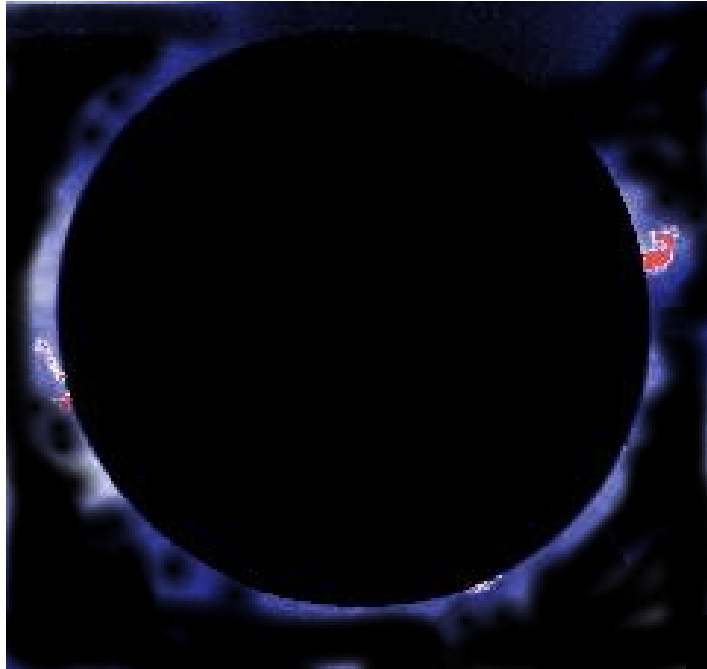$$T_{phot} \approx 5800 \text{ K}$$

Limb darkening: brightness of the photosphere decreases towards the edge (limb) of the sun; implies that the temperature increases towards the stellar interior
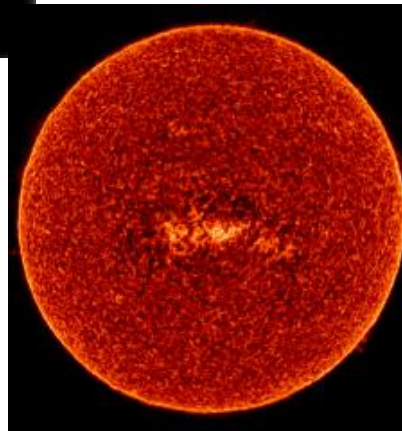
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The Chromosphere: Transition region

- Chromosphere: thin layer of stellar atmosphere just above photosphere.
- much fainter than the photosphere; can't be seen unless the photospheric radiation is blocked (eclipse, filter)
- much hotter than the photosphere: $6,000K < T < 20,000K$
- Emission lines produced (strong line, H-α 3-2 transition of H) makes chromosphere look reddish
- atmosphere structured: prominences
- just above the chromosphere is a transition region, where the temperature increases from $20,000K$ to $1,000,000K$

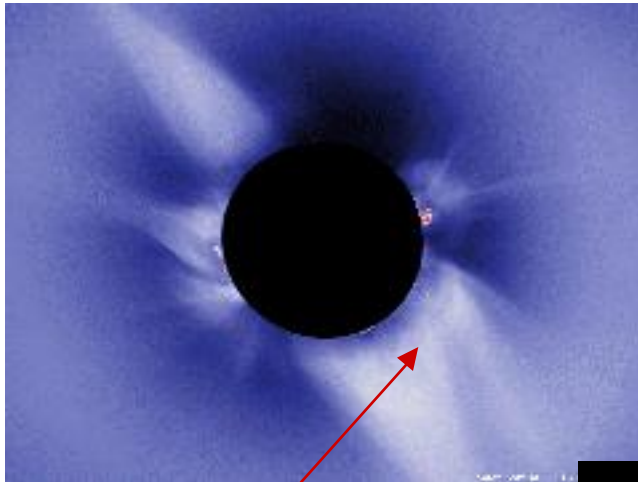Emission from the TR: S^{+5} emission at T=200,000 K
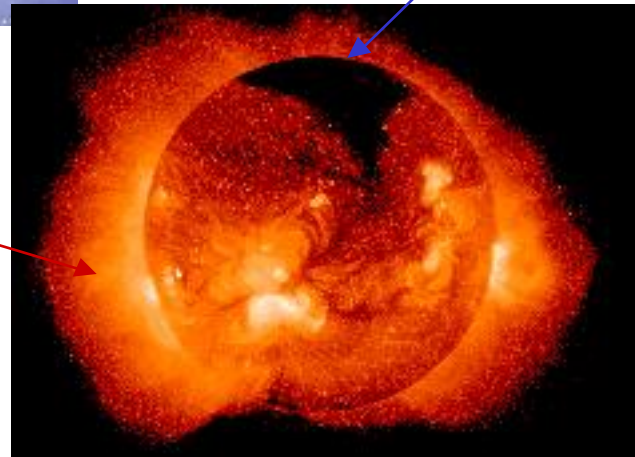
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The Corona: Extended outer atmosphere

- the corona is the most extended part of the solar atmosphere
- and also the hottest: $1,000,000 < T < 3,000,000$ for the sun
- visible during solar eclipses
- only observable part of the sun which produces X-ray emission
- non-uniform: coronal streamers and coronal holes
- solar wind emitted from coronal holes

coronal hole

corona

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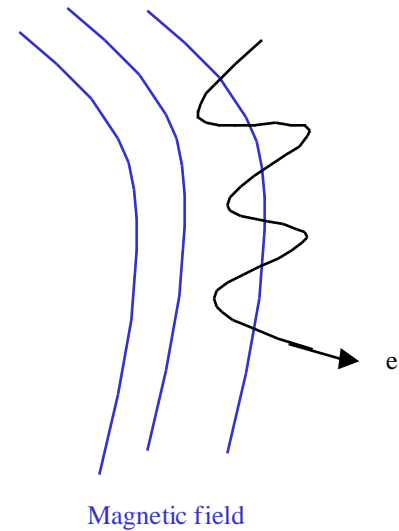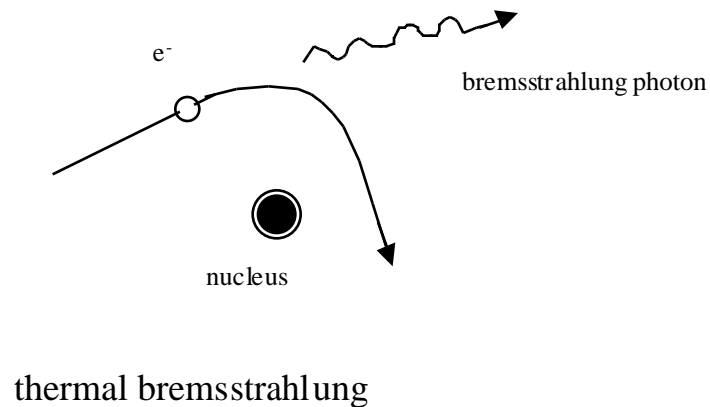301-286-5576

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Coronal Emission

- at temperatures of millions of degrees, the corona emits most strongly at X-ray energies

- gas in the corona is almost fully ionized (collisionally ionized since average particle speed is so high)

- emission consists of

  ➜ line emission due to recombination, collisional excitation + radiative de-excitation

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< Coronal continuum due to acceleration of free electrons:

- thermal bremsstrahlung (braking radiation)
- synchrotron radiation
- (inverse comptonization)

e⁻

bremsstrahlung photon

nucleus

thermal bremsstrahlung

Magnetic field

e⁻

Synchrotron emission

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XMM grating spectrum of
coronal emission from Capella
(G1 III + G8 III)

(Audard et al., A&A 365, L329-L335 (2001))
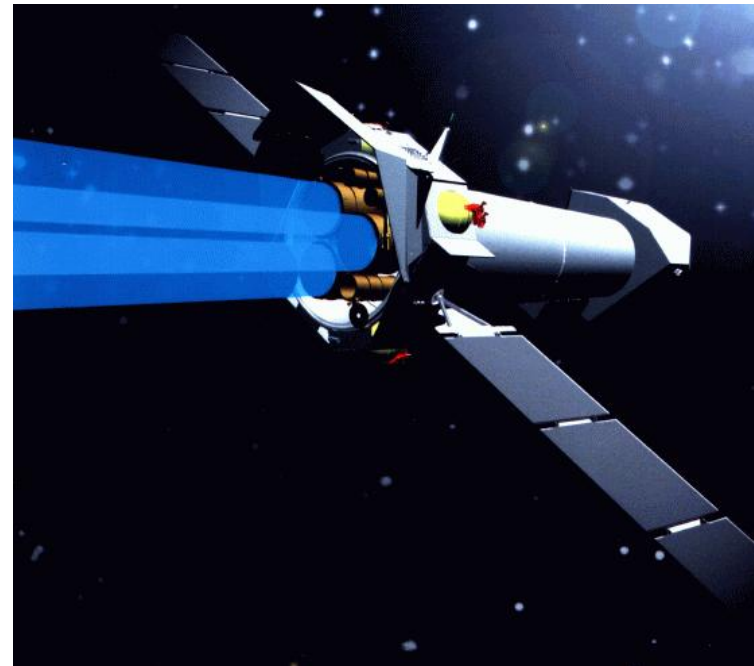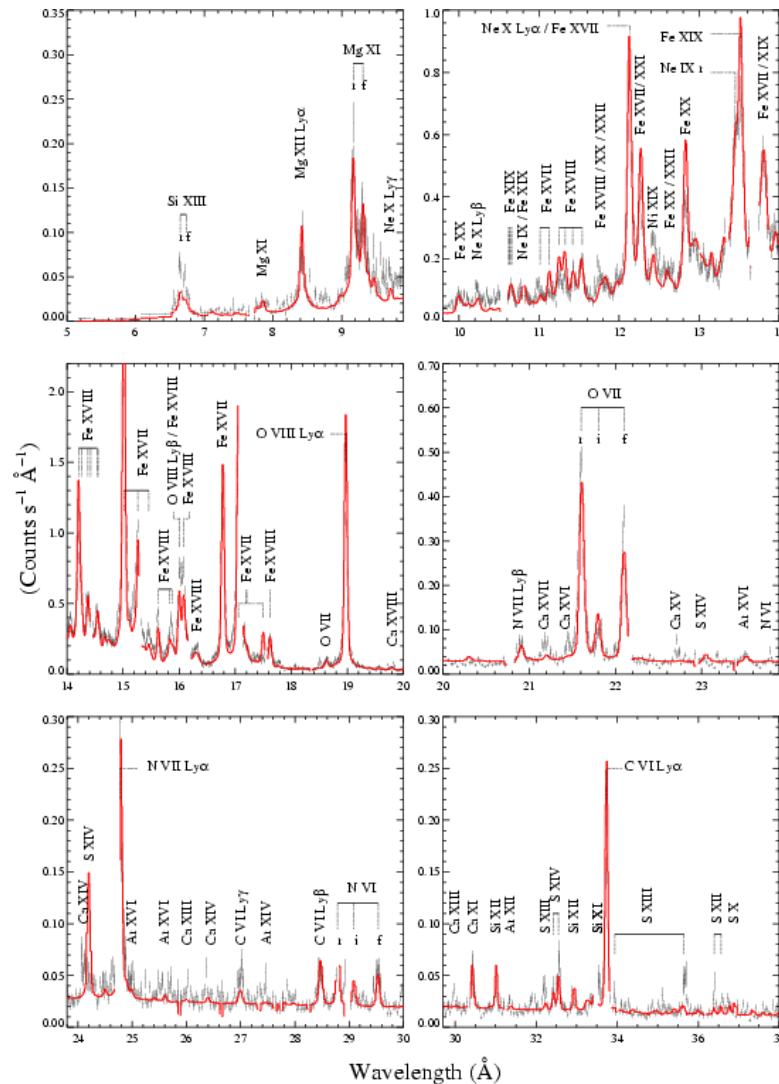
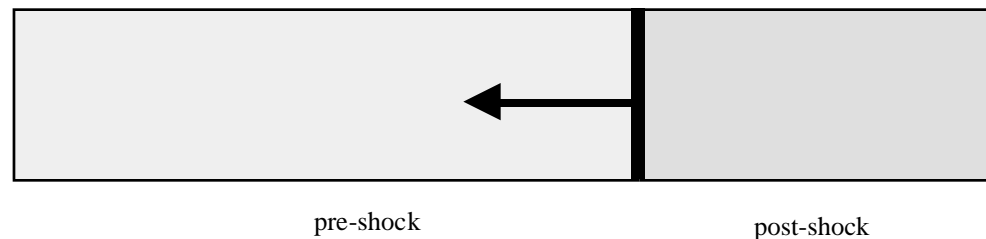February 1, 2001

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What Heats the Corona? 2 possible mechanism:

1. **acoustical heating**: sound waves carry energy from photosphere and chromosphere and deposit it in the corona via shock heating

pre-shock   post-shock

for an ideal gas and a strong shock(shock velocity >> sound speed c_s),
$$T_{\text{post-shock}} = 5/4\, M^2\, T_{\text{pre-shock}}$$
where M is the Mach Number $M = V_{\text{shock}}/c_s$

acoustical heating probably **not** too important in heating solar (or stellar) corona

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2. **Magnetic heating**: localized intensification of magnetic field can increase temperature

Magnetic field lines are "frozen" into the plasma; gas motions can twist the B field; in regions of high magnetic density, field lines can cross and "reconnect" releasing lots of energy
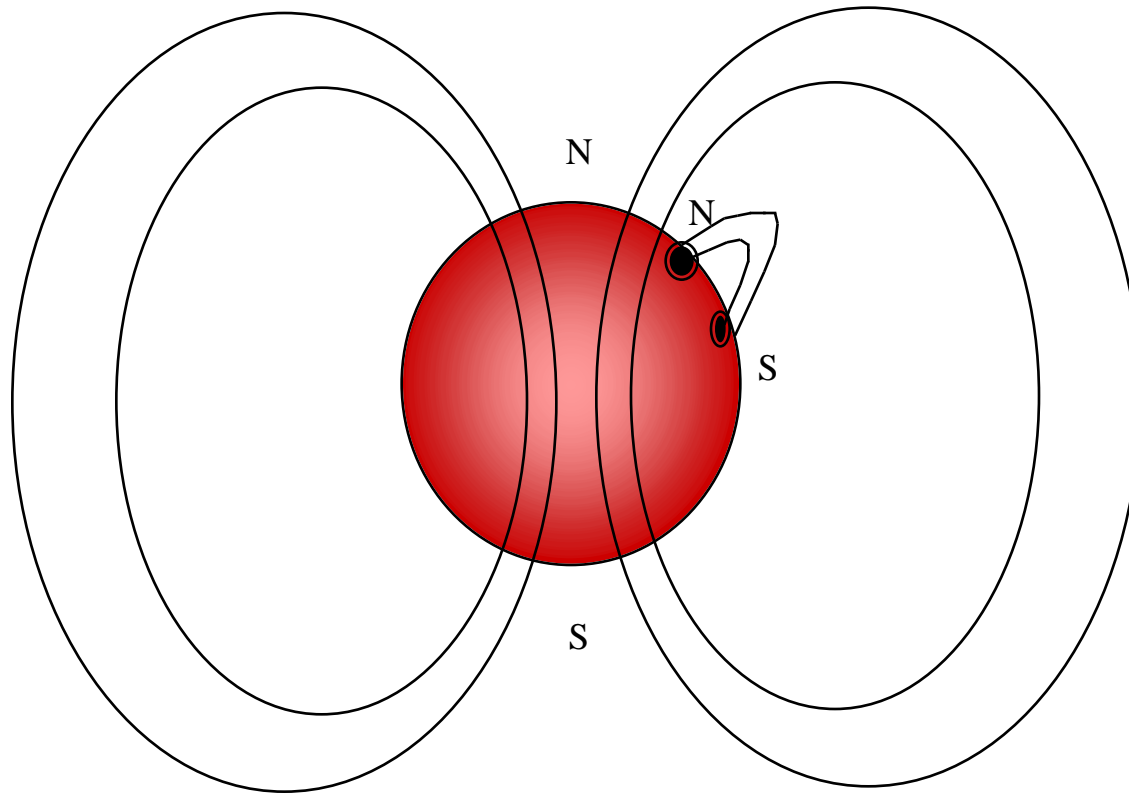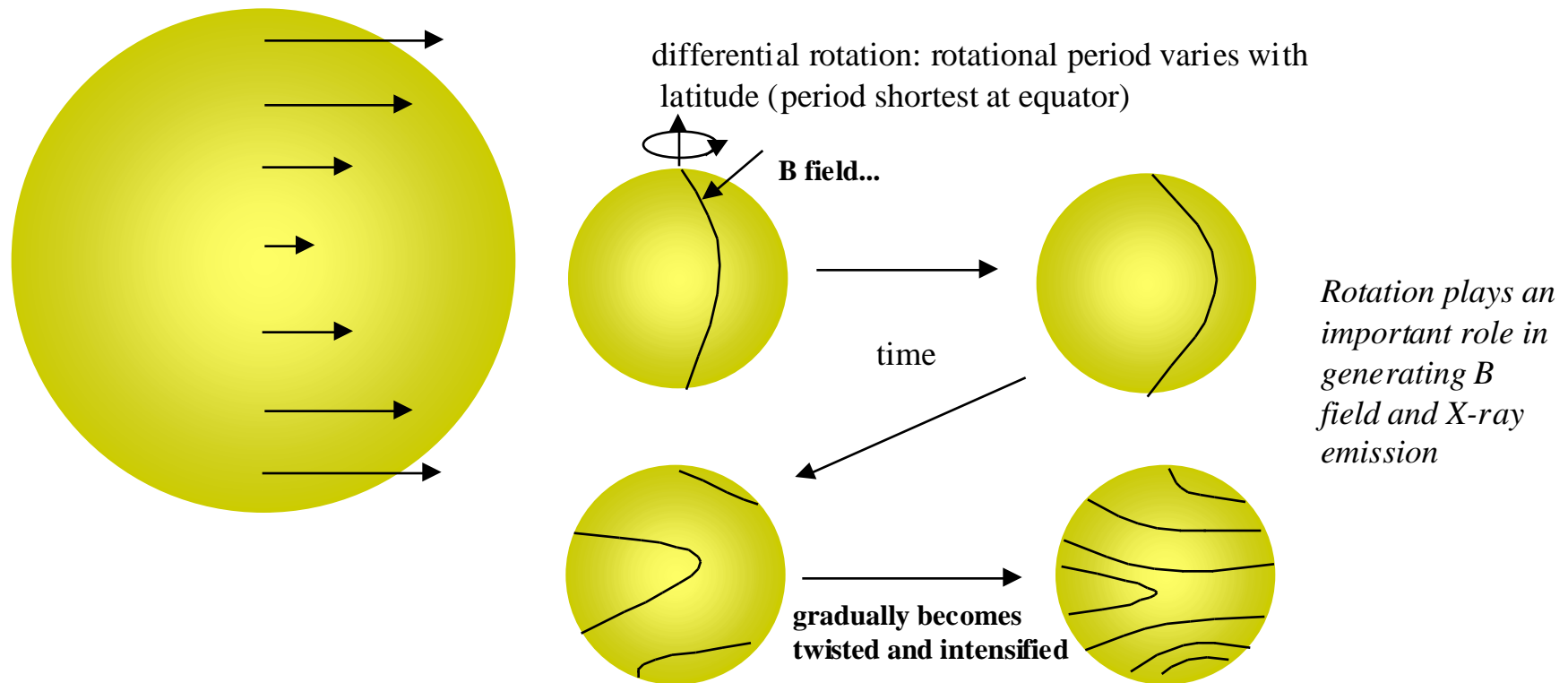
$$T = P/nk$$

$$P = P_g + P_B$$

$$P_B = B^2/8\pi$$

Magnetic heating thought to be the dominant heating mechanism in the corona (as the B field varies, the size and temperature of the corona varies too).

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Magnetic Fields and Stellar Activity Cycles

• Since the magnetic field is basically tied to the plasma, and since the plasma flows, rises and falls, and since stars do not rotate as solid bodies, the structure of the magnetic field is complex and dynamic

differential rotation: rotational period varies with latitude (period shortest at equator)

B field...

time

Rotation plays an important role in generating B field and X-ray emission

gradually becomes twisted and intensified

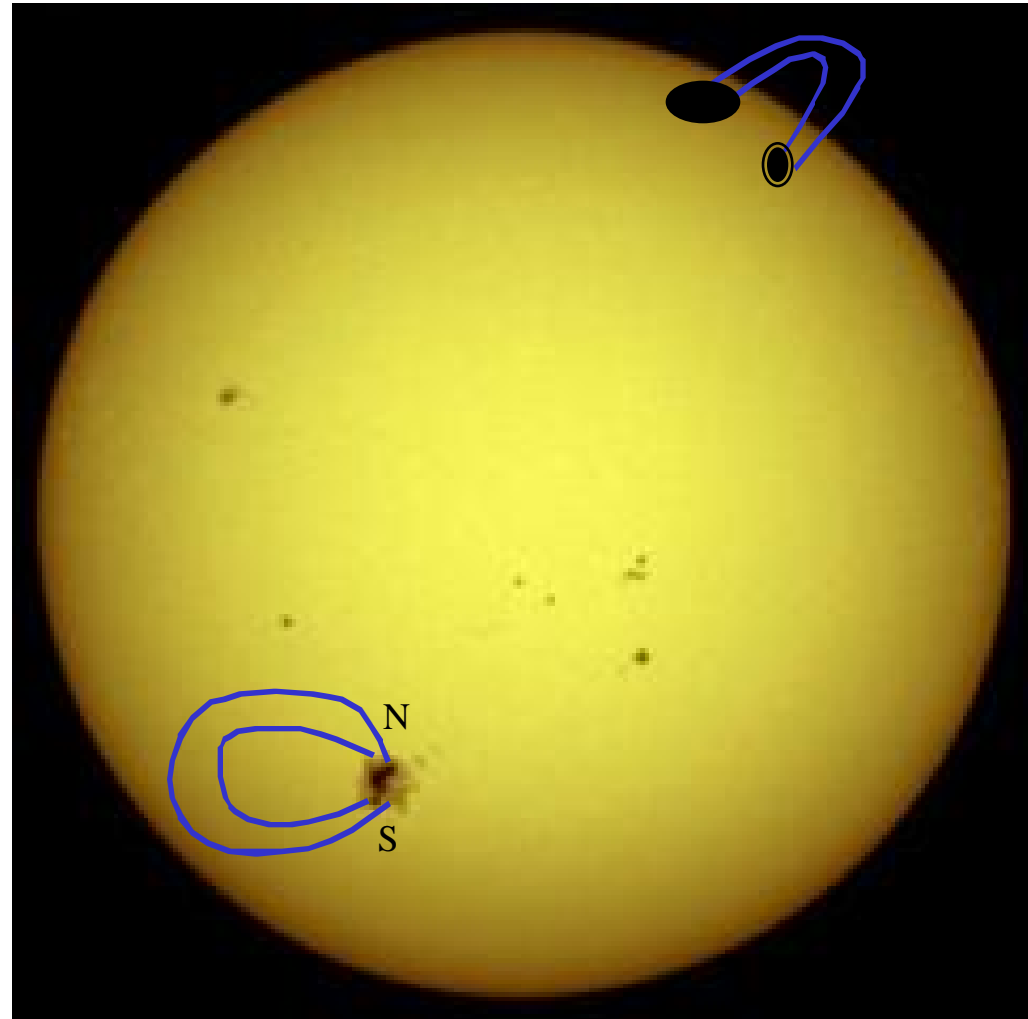February 1, 2001

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Twisted magnetic field can break through photosphere; footprint of the loop forms a **sunspot** pair, loop can carry plasma off the surface of the sun (**prominence**)

Violent intensification of B field can produce stellar **flares**

B field increases to a maximum then fades in an 11-year cycle (actual cycle is 22 years, since polarity reverses after one 11 year cycle)

Stellar X-ray flux varies with solar cycle; not yet clear if other stars have solar-type activity cycles

N

S

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Atmospheres of High Mass Stars (O & B stars)

• nearest OB type star is about 150 pc from earth: can't spatially resolve the structure of the atmosphere.

• UV spectra reveal photospheric emission (continuum emission + absorption lines) AND P-Cygni type spectral lines

redshifted emission

to earth

blueshifted absorption

redhifted emission

blue

red

wavelength
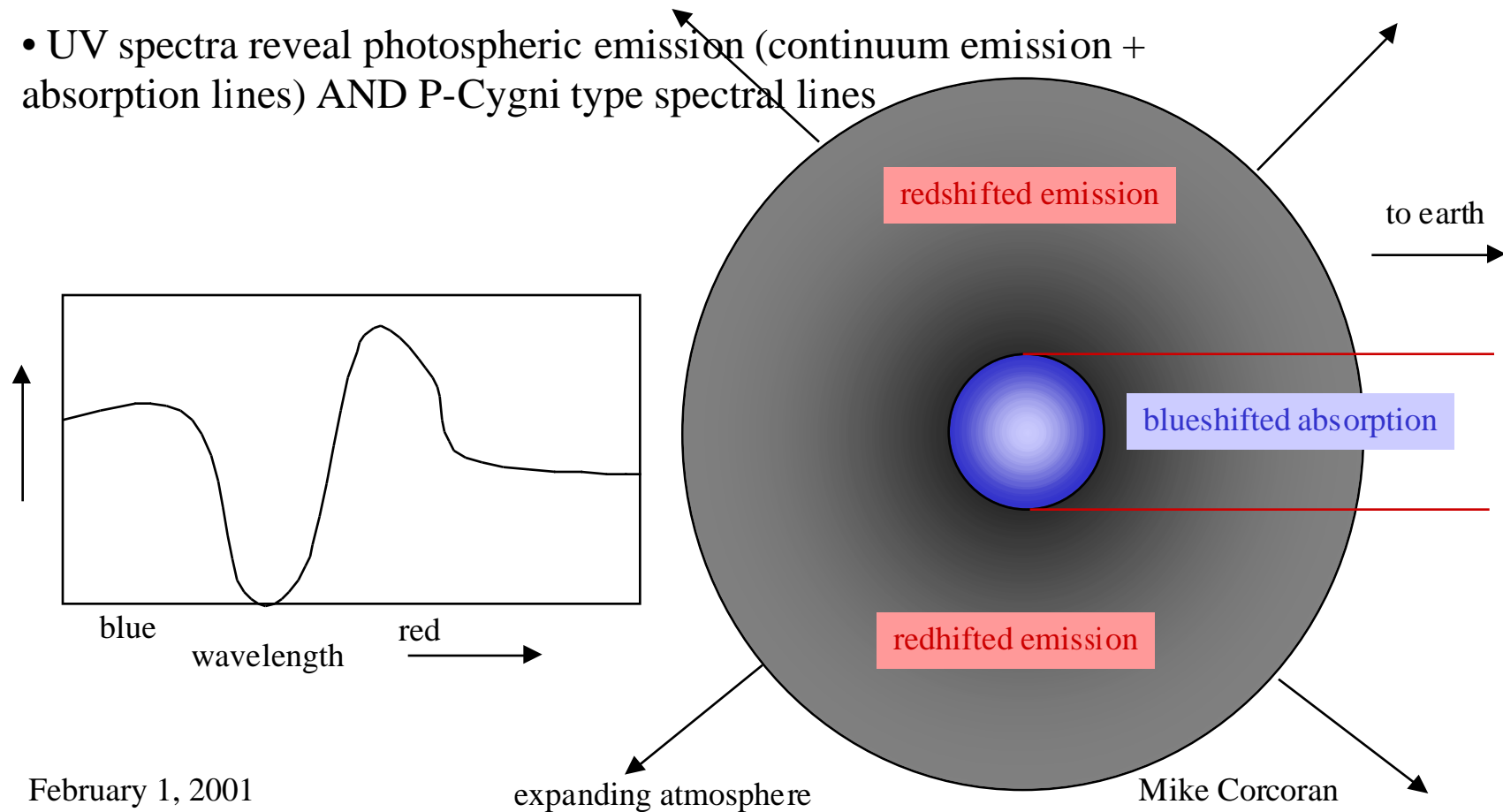
expanding atmosphere

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Atmospheres of OB stars

• presence of P Cygni profiles indicates an expanding outer atmosphere, a "stellar wind"

• Stellar wind continually carries away mass from star: mass loss rate $\sim 10^{-6} - 10^{-5}$ solar masses per year

• winds are fast: V $\sim$ 1500 – 3000 km/s

• wind speeds increase with distance from the star

• winds driven by the absorption of the intense radiation from the stellar photosphere by atoms in the stellar photosphere.

• radiative driving is **unstable**

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Assume a wind made up of a collection atoms of a single element and the wind is driven outward by absorption of photon momentum by atoms.

Assume that these atoms can absorb only photons of wavelength λ_o

if the atoms are moving away from the photon source with a non-relativistic velocity V then the atoms will see the photons from the source redshifted:

$$\Delta\lambda/\lambda_{rest} = V/c$$

$$\Delta\lambda = \lambda_{obs} - \lambda_{rest}$$

where λ_{rest} = rest wavelength of the photon and λ_{obs} the apparent wavelength seen by the atom

The atoms moving with velocity V will absorb photons with $\lambda_{obs} = \lambda_o$; these photons have a rest wavelength

$$\lambda_{rest} = \lambda_o/(1+V/c)$$

if the wind velocity of the atom is constant, then absorption of the material between the outer atoms and the star is constant; atom feels a constant "driving force"

if the wind velocity changes with distance from the stellar surface, then the amount of absorption changes as the atom accelerates due to the doppler shift, so the amount of momentum transferred to the atom changes too. This coupling between the driving force and the motion of the atoms causes the driving force to be **unstable** to small perturbations.

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X-ray emission from OB stars

- OB stars were discovered as X-ray sources by the EINSTEIN observatory (first emission seen from Cyg OB2, and OB association in Cygnus)

- $L_x \sim 10^{-7} L_{bol}$ (but $L_{bol} \sim 10^6 L_{sun}$)

- Emission is thermal (thermal lines plus bremsstrahlung continuum)

- Presumably produced by shocks distributed through wind (typically X-ray emission is not time variable)

- early suggestions of 'thin coronal layer" just above photosphere initially ruled out by lack of significant absorption by wind; recent observations of emission line X-ray spectrum may suggest that some of the emission at least does occur near the photosphere)

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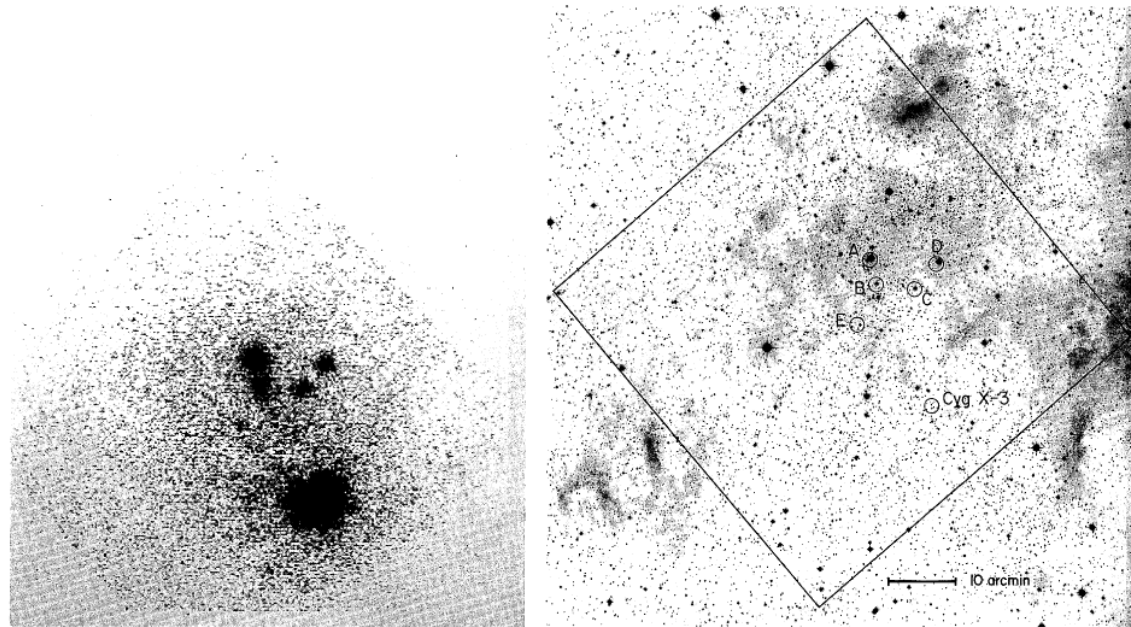301-286-5576

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FIG. 1.—Region observed during the first exposure to the X-ray sky with the imaging proportional counter (IPC) of the *Einstein* Observatory. North is up and east is to the left in each portion of the plate. (*a*) Arcmin-resolution X-ray image; the gray scale is approximately logarithmic, with denser and darker regions corresponding to higher 0.2–4 keV X-ray intensity. The bright source at lower right is Cygnus X-3. The composite image, containing ~10⁴ s of data, is a superposition of 11 separate exposures of a region which fortuitously includes the OB star association. (*b*) Reproduction of the Palomar Sky Survey red print, with the X-ray locations (labeled A through E and Cyg X-3) superposed as ~1′ radius circles; the scale is indicated at the lower right. The large trapezium of stars (A–D) consists of the four most luminous stars of the VI Cygni OB association.

HARNDEN *et al.* (*see* pages L51 and L52)

EINSTEIN discovery of X-ray emission from Cyg OB2 O stars
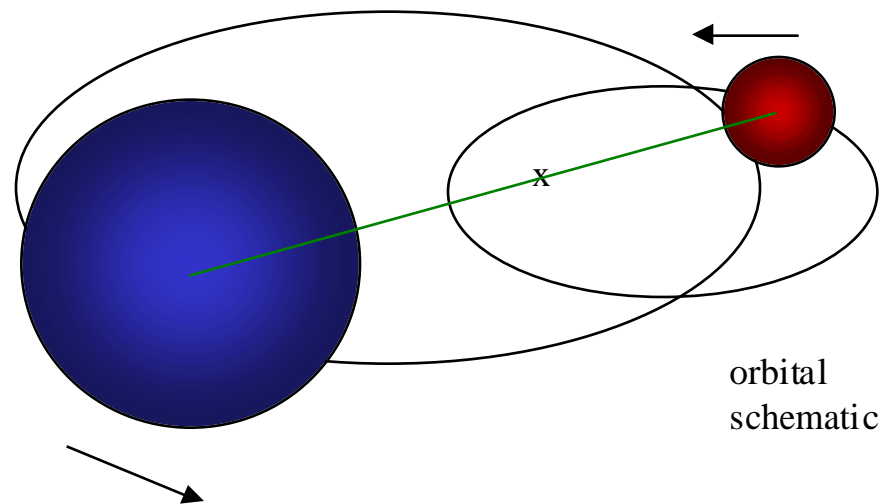Harnden et al. 1979, ApJ, 234, L51

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Stellar Interactions

- stars not only form in groups, they form in pairs.

- if the 2 stars are close enough, they can interact:

  - gravitational (tidal) interactions

  - magnetic interactions

  - wind-wind collisions

x

orbital
schematic

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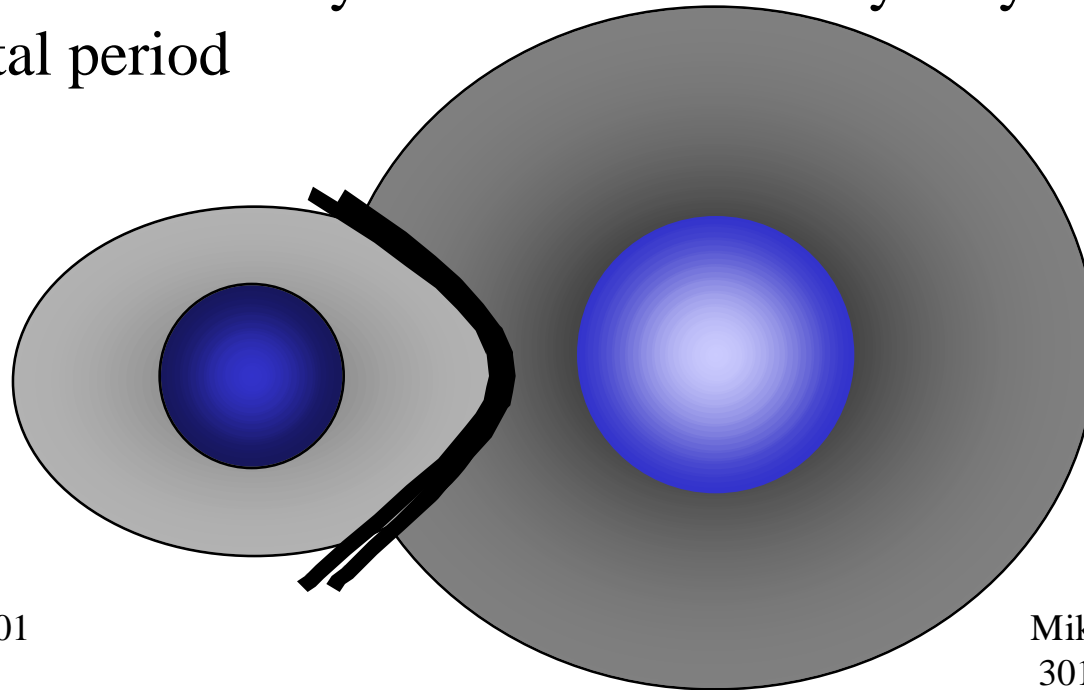301-286-5576

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Magnetically Interacting Stars: RS CVn binaries

- RS CVn stars are close binaries (Periods of days) consisting of two magnetically active low mass stars
- tidal interactions cause the 2 stars to be co-rotate (rotation period = orbital period)
- this causes the stars to spin rapidly and enhances the magnetic activity of the stars
- intense magnetic fields produce large starspots (can cover 20-50% of stellar surface)
- large prominences; B field from one star may connect to B field of other star
- intense X-ray sources (time variable flares)

Wind–Wind Interactions

- For massive stars in binaries, wind from one star can collide with wind or surface of companion

- produces strong shock between the stars

- shock produces X-ray emission which may vary with orbital period

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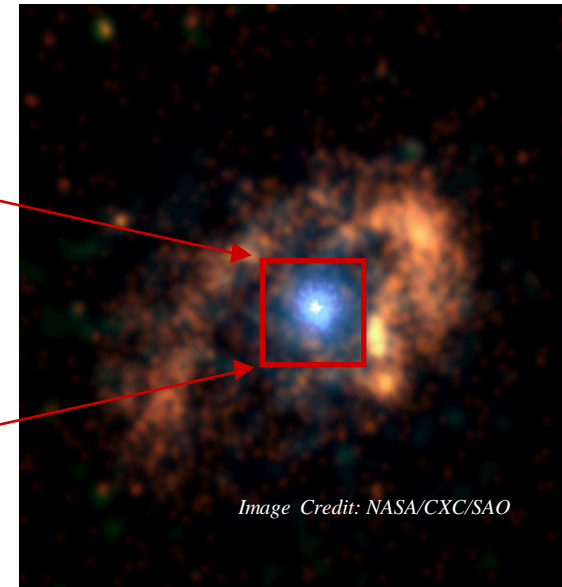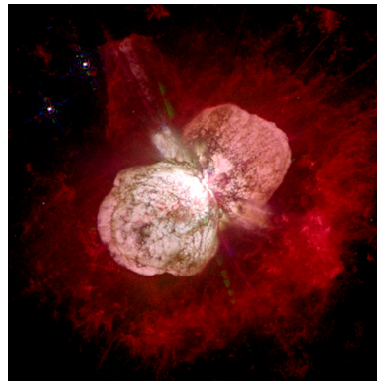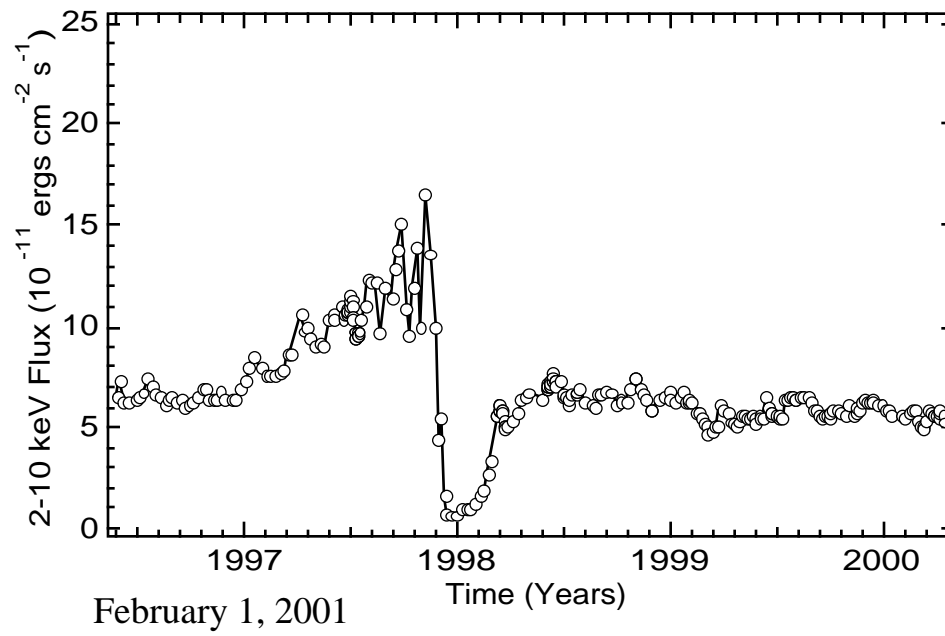
Variable X-ray emission from Eta Carinae

Image Credit: NASA/CXC/SAO

- Eta Carinae: extremely massive unstable star
- discovered as an X-ray source by EINSTEIN
- discovered as a variable X-ray source by ROSAT
- detailed X-ray variations seen by RXTE indicates presence of a companion star

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